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13. ABSTRACT *(Maximum 200 Words)*
The current research was conducted to demonstrate that a new NDE method based upon thermoelasticity can be utilized to quantify damage in composite materials, to identify damage mechanism, and to be generally applicable as a lifetime prediction tool. Funding from the DURIP award was used to purchase an IR camera system and a photoelastic imaging system. The IR camera is a Stress Photonics DeltaTherm1000 closed cycle cooled system with a temperature resolution of 0.003K at a spatial resolution of 120 microns. A sapphire zoom lens was purchased to improve the resolution to 20 microns. A broad range of experiments were carried out to characterize local damage and stress concentrations in several composite systems. Experimental measurements of damage and the resulting stress distributions across the surface of test specimens were used to quantify damage evolution in each composite material. Damage evolution was quantified by using experimental measures of stress concentration factors derived from the observed IR signal. These measures of damage were used to relate changes in the composite properties to the experimentally measured stress redistribution. We found that the system could identify the operative damage mechanism, the current state of damage, and predict the residual fatigue lifetime of the tested materials. As a result, a new method has been developed for evaluating and tracking damage in composite materials and for accurately predicting the remaining service lifetimes of those materials.

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THERMOELASTIC NON-DESTRUCTIVE EVALUATION OF STRUCTURAL MATERIALS

Summary Report
AFOSR

GRANT # F49620-99-1-0215

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Introduction and Overview

One of the major attributes of fiber reinforced composites is the existence of inelastic mechanisms that allow for stress redistribution around sites of strain concentration.[1-4] These mechanisms involve combinations of matrix cracking, fiber debonding and fiber pull-out. The operative damage mechanism is known to depend upon the micromechanical properties of the composite, suggesting an important possibility: changes in any of the constituent properties can change the operative damage mechanism in a material. The current research was conducted to demonstrate that a new NDE method based upon thermoelasticity can be utilized to quantitfy damage in composite materials, to identify the damage mechanism, and to be generally applicable as a lifetime prediction tool. Funding from the subject DURIP award was used to purchase an IR camera system as well as a photoelastic system to enable damage mapping in composite materials.

A range of experiments were carried out to characterize local damage and stress concentrations in several composite systems. Experimental measurements of both the stress and strain distributions across the surface of test specimens were used to quantify stress redistribution during damage evolution in several different composite materials. The damage evolution is quantified by using notch sensitivity parameters as well as experimental measures of stress concentration factors.[2] These measures of damage were used to relate changes in the composite properties to the experimentally measured stress redistribution.

Accomplishments

The following tasks were accomplished:

(1) A new damage imaging method was developed to measure macroscopic damage evolution and it's effect on the stress distribution in composites. The method was applied to a broad range of composites to demonstrate the general utility of the approach. The composites analyzed include: glass/Portland cement, alumina/alumina; C/SiC, glass/epoxy, glass/polyurethane, laminated polymer membranes of polyurethane and EVOH and polyethylene and PVDC.

(2) A new fatigue lifetime prediction model was developed to estimate the residual fatigue lifetime of impact-damaged polymer composites.

(3) Initial experiments were conducted to show that the method can be made field portable and used to assess battle damage in composite materials (e.g. aircraft wing skins).

(4) Experiments on glass/epoxy composites have shown that the damage mechanism can be changed by changing the interfacial properties in the composite.

(5) The IR method was extended to measure the onset of *sub-surface* cracking in laminated composites. This method can now be utilized to measure the debonding of coatings, sub-surface cracking in layered systems, including microelectronic packages and MEMs devices

(6) The method was used to evaluate machining damage in composites and clearly shows differences in machining methods.

Presentations and publications

The following presentations and publications resulted from research funded through the present project for the time frame 10/99-9/00:

Presentations (10/99-9/00)

N. R. Sottos and T.J. Mackin, "Tailoring Interfacial Toughness in Model Composites for Improved Damage Tolerance" To be presented at the 15th Annual Technical Meeting of the American Society for Composites, College Station TX, Sept. 23, 2000.

T. J. Mackin, "The use of Thermoelastic Stress Analysis to Measure Damage Evolution and Stress Redistribution in Composites," seminar presented at U-Conn, October 1999.

T. J. Mackin, "Using Thermoelasticity to Evaluate Stress Redistribution in Composites," Invited lecture at the 24th annual Cocoa Beach Conference and Exposition, January 2000.

T. J. Mackin , "The Effect of the Interphase on Damage Evolution in Model Composites," presented at the 24th annual Cocoa Beach Conference and Exposition, January 2000.

D. W. Gardner and T. J. Mackin, "On the Resolution Limits of Thermoelastic Stress Analysis," presented at the annual meeting of the Society for Experimental Mechanics, Orlando, Fl, June 5-8, 2000.

G. Horn, T. J. Mackin, and P. Kurath, "Quantifying Machining Damage in Polymer Composites," presented at the annual meeting of the Society for Experimental Mechanics, Orlando, Fl, June 5-8, 2000.

M. X. Brandi and T. J. Mackin, "Infrared Imaging of Slip Zones in a Model Fretting Geometry," presented at the annual meeting of the Society for Experimental Mechanics, Orlando, Fl, June 5-8, 2000.

N. R. Sottos and T.J. Mackin, "Tailoring Interfacial Toughness in Model Composites for Improved Damage Tolerance" To be presented at the 15th Annual Technical Meeting of the American Society for Composites, College Station TX, Sept. 23, 2000.

Conference Proceedings (10/99-9/00):

N. R. Sottos and T.J. Mackin. Tailoring Interfacial Toughness in Model Composites for Improved Damage Tolerance. In Proceedings of the 15th Annual Technical Meeting of the American Society for Composites, Technomic, to appear, (2000).

D. W. Gardner and T. J. Mackin, "On the Resolution Limits of Thermoelastic Stress Analysis," Proceeding of the Society for Experimental Mechanics, Orlando, Fl, June 5-8, 2000.

G. Horn, T. J. Mackin, and P. Kurath, "Quantifying Machining Damage in Polymer Composites," Proceeding of the Society for Experimental Mechanics, Orlando, Fl, June 5-8, 2000.

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Transitions

The damage evolution method developed herein is currently being used at NASA Glenn Research Center. The method is being used to develop high temperature materials for combustors. The contact person at NASA Glenn is Greg Morscher.

Journal Publications

Meyer, L. J., T. J. Mackin, and J. Mott, "Mechanical Properties of a Filament Wound Glass Fiber Reinforced Portland Cement Composite," *Concrete Science and Engineering*, Vol. 2, December 2000, pp. 196-205.

Mackin, T. J. and M. C. Roberts, "Evaluation of Damage Evolution in Ceramic-Matrix Composites Using Thermoelastic Stress Analysis," *Journal of American Ceramic Society*,**83**[2] 337-43 (2000).

Mackin, T. J., "Stress Redistribution in Ceramic Matrix Composites," in *Advanced Engineering Materials*, Vol. 2, No. 12, December 2000.

Horn, G., Mackin, T. J., and Kurath, P., "Estimating Residual Fatigue Lifetimes of Impact Damaged Composites Using Thermoelastic Stress Analysis," *Polymer Composites*, Vol. 41, No. 3, March 2001.

Mackin, T. J., Halverson, T. L., and Sottos, N. R., "The Effect of Interfacial Properties on Damage Evolution in Model Composites," submitted to *Journal of American Ceramic Society.*

Mackin, T. J. and Vernon, P. E., "Detecting Sub-Surface Cracking in Laminated Membranes Using Infrared Imaging," accepted for publication in *Polymer Composites.*

Horn, G., Mackin, T., and Kurath, P., "Using thermoelasticity to quantify machining damage in composites," accepted for publication in *Polymer Composites.*

Conference Publications related to this grant (10/99-9/00):

N. R. Sottos and T.J. Mackin. Tailoring Interfacial Toughness in Model Composites for Improved Damage Tolerance. In Proceedings of the 15th Annual Technical Meeting of the American Society for Composites, Technomic, to appear, (2000).

Summary of Results

Damage Evolution in Model Composites

Model composites consisting of unidirectional glass fibers in an epoxy matrix were utilized to study the effect of composite constituent properties on damage evolution in brittle matrix composites. The fiber/matrix interface was altered by adding coupling agents to the matrix resin. Dow Corning® Silanes Z6032 and Z6070 were utilized to enhance or weaken the interface bond, respectively. The statistical strength properties of the fibers were altered by using Owens-Corning® fiberglass with two different surface coatings: 636 glass fiber utilizes a standard starch coating, while 646 glass fibers have a coating of starch plus an added silane. Thermoelastic stress analysis was used to map stress redistribution as a result of damage evolution during loading.

The addition of coupling agents was found to have no significant effect on the baseline mechanical properties of the epoxy matrix composites with either 636- or 646-type glass fibers. However, notable differences arise when comparing the untreated composites with 636- and 646-type glass fibers. The 636-type composites developed multiple matrix cracks, while the 646-type composites developed shear bands. The addition of an interface weakening agent shifted the damage mechanism from multiple matrix cracking to the development of shear bands in the 636-type glass/epoxy, Figure 1.

A Novel damage imaging method was developed to provide an accurate identification of the operative damage mechanism. The method involves capturing images that lag the applied load by a phase angle of 90 degrees. Such images include temperature effects related to hysteretic dissipation and can be utilized to provide a detailed image of the locations of damage in a composite. This method was used to capture a sequence of damage images for both the 636 and 646-type composites, Figure 2. These images clearly show the presence of multiple matrix cracking in the 636 composite and shear bands in the 646 composite.

The effect of damage on residual life

Composites will experience a wide range of loading when implemented into service applications. A key issue in many applications is the effect of impact damage on the residual fatigue lifetime of a composite. In general, the fatigue lifetimes of composites are known to decrease with increasing impact energy. Though this relationship is intuitive, it is not practical for engineering design since the magnitude of the impact energy is not generally available.

Recent work at UIUC has utilized TSA to provide thermoelastic stress maps of impact-damaged composites to assign a stress concentration factor to the impact site. The methodology is amenable to in-situ inspection of structural components and provides an objective, quantitative assessment of damage. Typical optical and TSA images of impact-damaged glass/epoxy and glass/polyurethane composites are shown in Figure 3. These composites exhibit two extreme behaviors: glass/polyurethane develops *macrocracking* while the glass/epoxy exhibits a diffuse damage zone accompanied by *delamination.* These sorts of impact-damage result in a great deal of scatter in the resulting fatigue lifetimes, Figure 4a. However, if the applied stress amplitude is multiplied by the mSCF obtained from TSA imaging the resulting fatigue lifetimes collapse onto master curves, Figure 4b.

In order to predict the residual fatigue lifetime of a service component, one would scan the component, determine the mSCF associated with the impact site, find the effective stress amplitude, and read the lifetime from a previously acquired SN curve. This method provides a quantitative measure of the current damage state while it enables a simple means for estimating residual life. At this point the method has been applied to polymer matrix composites and has not yet been extended to CFCCs.

Conclusions

Model composites were utilized to explore the effect of interface properties on damage evolution. Direct measurements of interface properties were conducted by performing push-out tests on model composites. The mode II fracture energy as well as the interface friction were altered by fiber surface roughness and coupling agents. Damage evolution was explored using model composites fabricated using 636-type and 646-type glass fibers in epoxy. The 636-type glass/epoxy composites exhibited multiple matrix cracking, while 646-type glass fiber composites developed shear bands. This result is notable since the composites that developed shear bands exhibited the same failure strains but 40% higher ultimate strengths when used in a matrix without coupling agents. Adding coupling agents to the epoxy resin altered the interface in both composites. Coupling agents did not alter the damage mechanism in the 646-type glass/epoxy composites, however, the addition of a weakening agent to the 636-glass/epoxy changed the damage mechanism from multiple matrix cracking to shear band formation. These experiments clearly demonstrate that the operative damage mechanism can be changed through controlled interface properties.

Air Force Relevance

Continued improvements in thrust-to-weight ratios depend upon the development of new materials that are lighter, stiffer, and stronger at elevated temperatures. In order to implement new composites, it is important to understand how stress concentrations, such as holes, notches, lap joints, and incidental damage will affect the residual strength and lifetime of the proposed composite system. The current research is developing new methods to image and quantify stress concentration and damage in composites. In addition, the present research is using new experimental methods to relate micro-mechanical properties to damage evolution and lifetime prediction in new composite materials.

Acknowledgement/Disclaimer

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FIGURES

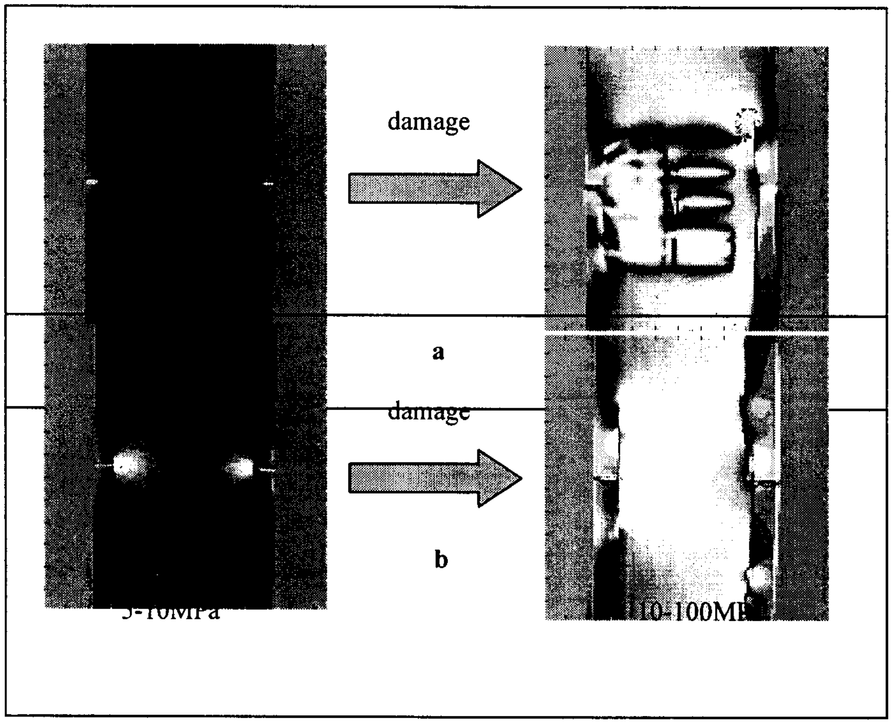


Figure 1. The effect of surface treatments on damage evolution in the 636-glass/epoxy composite; (a) The addition of a strengthening agent (6073) did not change the damage mechanism; while (b) the addition of a weakening agent (6070) changed the damage mechanism to the formation of shear bands.

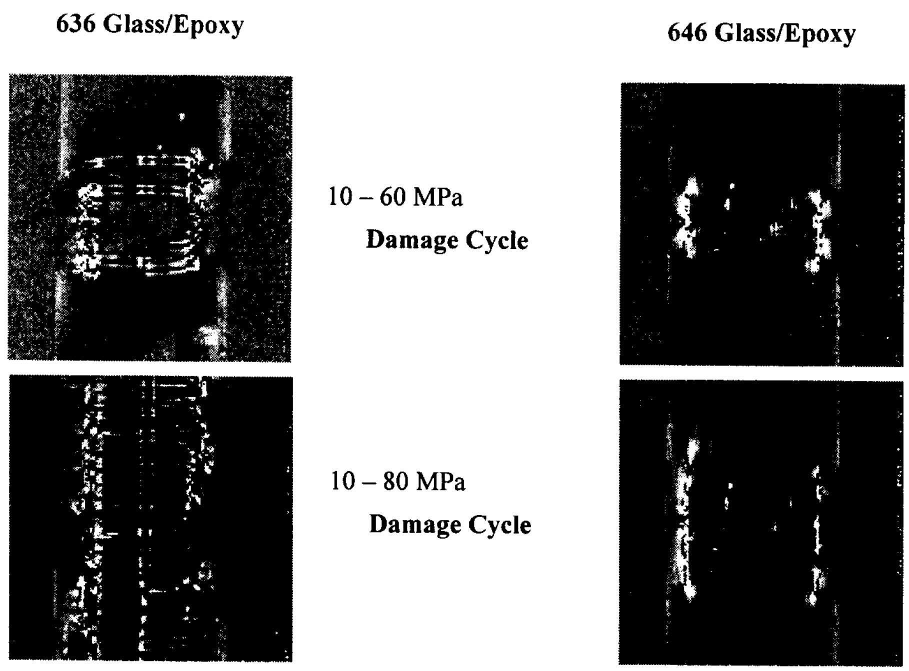


Figure 2. Damage images of the model glass/epoxy composites. Damage in the 636-glass/epoxy evolves as multiple matrix cracks (Left images), while damage in the 646-glass/epoxy evolves as shear bands (right images).

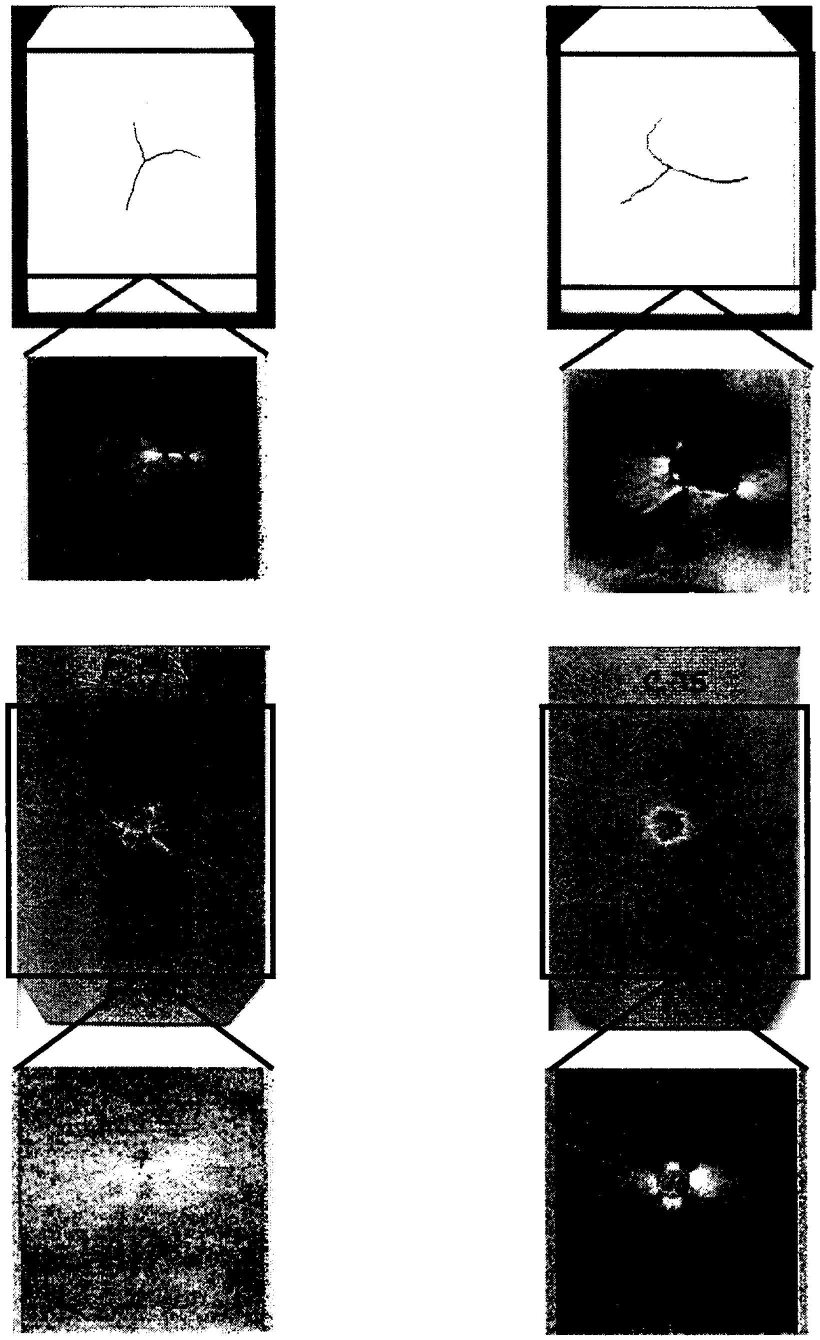
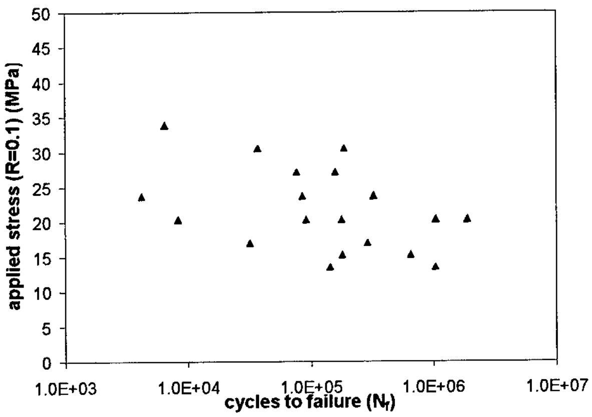


Figure 3. Optical (upper) and thermoelastic images (lower) of impact-damaged samples. (a) Glass/polyurethane; (b) Glass/epoxy.



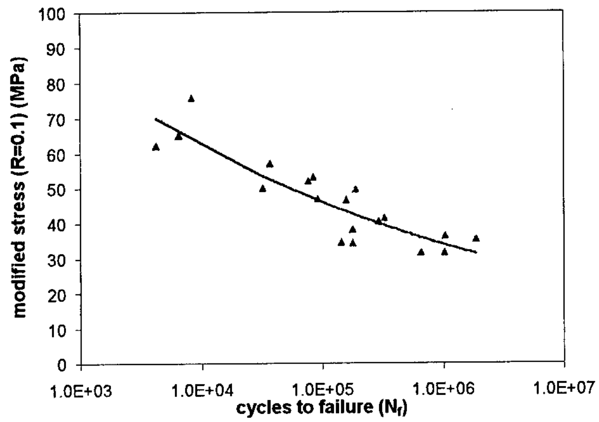


Figure 4. Plot of impact-fatigue data for glass/polyurethane samples. (a) The raw data show no discernible trend in S-N space, while (b) an S-N plot that utilizes the TSA-derived effective stress collapses the data in (a) onto a master curve.